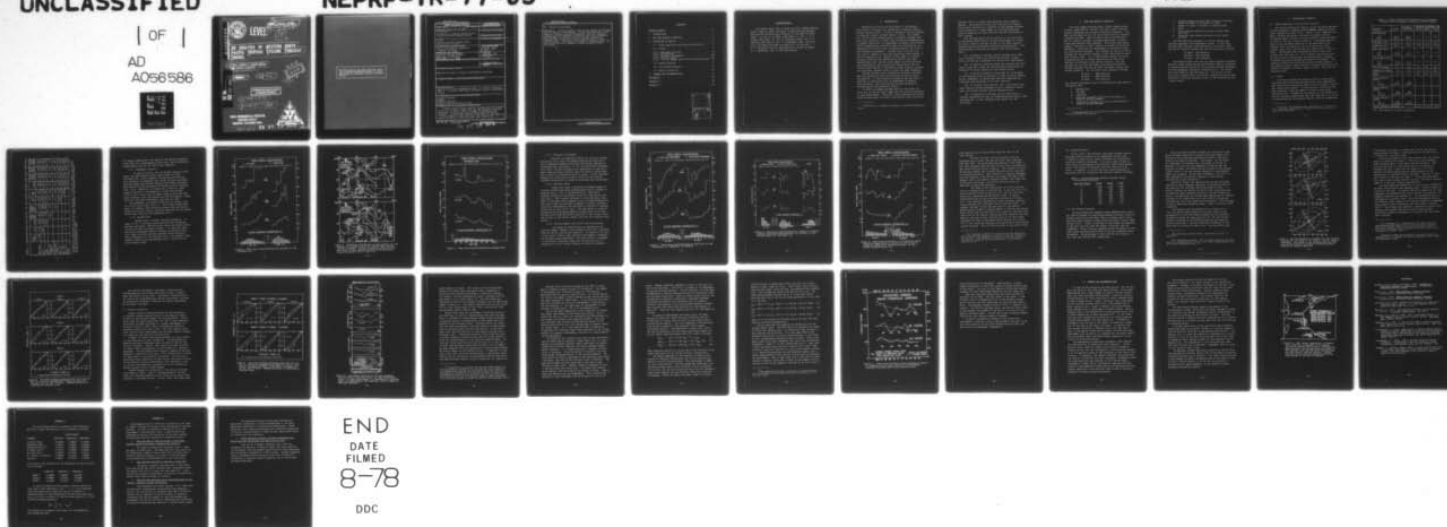AD-A056 586   NAVAL ENVIRONMENTAL PREDICTION RESEARCH FACILITY MON--ETC F/G 4/2
AN ANALYSIS OF WESTERN NORTH PACIFIC TROPICAL CYCLONE FORECAST --ETC(U)
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TECHNICAL REPORT
NEPRF-TR-77-05

AN ANALYSIS OF WESTERN NORTH PACIFIC TROPICAL CYCLONE FORECAST ERRORS.

JERRY D. JARRELL, SAMSON BRAND
DONALD S. NICKLIN

NOV 77

42p.

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NAVAL ENVIRONMENTAL PREDICTION
RESEARCH FACILITY
MONTEREY, CALIFORNIA 93940

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REPORT DOCUMENTATION PAGE	READ INSTRUCTIONS BEFORE COMPLETING FORM

1 REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
Technical Report No. 77-05		

4. TITLE (and Subtitle)	5. TYPE OF REPORT & PERIOD COVERED
An Analysis of Western North Pacific Tropical Cyclone Forecast Errors	
	6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)	8. CONTRACT OR GRANT NUMBER(s)
Jerry D. Jarrell, Samson Brand and Donald S. Nicklin	

9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
Naval Environmental Prediction Research Facility Monterey, CA 93940	PN 7W051 CC00 WU #6.3-2

11. CONTROLLING OFFICE NAME AND ADDRESS	12 REPORT DATE
Naval Air Systems Command Department of the Navy Washington, D.C. 20361	November 1977
	13. NUMBER OF PAGES
	41

14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)	15. SECURITY CLASS. (of this report)
	UNCLASSIFIED
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Tropical Cyclones
Typhoon
Strike Probability
Tropical Cyclone Forecast Errors

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Western North Pacific tropical cyclone position forecast errors for 10 years (1966-1975) are statistically analyzed. Variations of errors versus a number of parameters are examined. Discriminant analysis techniques are used to isolate categories where forecasts are likely to be above and below the median in west-east and north-south error

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20. Abstract (continued)

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components. The discriminant analysis was tested on 1976 data and the results are presented. It was confirmed that a small number of readily available parameters (such as location, maximum wind and components of motion) can, with reasonable effectiveness, classify a tropical cyclone forecast as representing a group with either markedly above or below average errors. The annual variations of forecast errors are also discussed and an attempt is made to explain those variations.

CONTENTS

ACKNOWLEDGMENTS

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1. INTRODUCTION

Operational military decision makers in the western
North Pacific routinely use information on average tropical
cyclone forecast errors in order to determine actions required
to evacuate, evade or protect against storms. For example,
U.S. military staff meteorologists incorporate average fore-
cast error statistics in their decision-making recommendations
of typhoon conditions[1] for Department of Defense installations.
These recommendations therefore impact the planning for the
evacuation of aircraft from a threatened base or the level of
base shutdown preparedness. Average error statistics are
also used in regards to decisions concerning ships whether in
port or evading at sea. Because of the number of tropical
cyclones traversing the western North Pacific each year
(approximately 35), and the large number of ports and bases
and installations used directly and indirectly by the U.S.
military which may be in the paths of these tropical cyclones,
such decisions, whether right or wrong, are made frequently.

Average forecast error information currently available
does not provide the most accurate decision-making inputs
now possible. If more accurate information was available it
could be of significant value to Department of Defense
decision makers, and could provide valuable guidance on
optimum evasion and evacuation tactics.

It should be emphasized that decision lead times for
ships are, of course, much longer than for aircraft evacuation
or base preparedness. Ships have to get underway well before
winds and seas start to affect significantly their ability to

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[1]*Conditions of readiness relating to expected destructive
winds.*

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maneuver clear of a harbor and thereafter their speed-of-advance. Since decision errors are a function of forecast errors which increase as a function of time between forecast and verification, a larger number of incorrect decisions could be expected for ships than for aircraft evacuations or base closures.

Thus the need exists for an analysis of the variations in the western North Pacific forecast performance for different areas, times of the year as well as for those tropical cyclones having recognizably different characteristics. This study attempts to do such an analysis with the following goals:

(a) To develop a tropical cyclone forecast error data set to provide a basis for statistical analysis of past errors and provide a benchmark for future error improvements.

(b) To identify situations where the forecasts are very good or very bad in order to allow maximum concentration of resources for quick reduction of the largest errors.

(c) To provide probability algorithms for an estimate of the forecast errors of warnings in order to assist western Pacific commanders in operational decisions regarding the protection and evacuation of military resources.

(d) To stratify errors for 24-, 48-, and 72-hour forecasts based on various parameters such as location, time of year, and various tropical cyclone characteristics.

(e) To determine if the year to year variations in forecast accuracies are real or random deviations about a long term mean and, if real, determine the reasons for the variations.

2. DATA AND METHOD OF ANALYSIS

The Joint Typhoon Warning Center (JTWC), Guam provided
10 years (1966-1975) of forecast and "best track"[2] tropical
cyclone information for the basic statistical analysis. The
data set included the 24-, 48- and 72-hour official forecasts
issued by the JTWC. 6150 six-hourly best track positions
for 317 tropical cyclones (including depressions, tropical
storms and typhoons) were examined. There were some storms,
however, that were so short-lived as to provide no verifying
forecasts. These were not represented in the data set that
was statistically analyzed. For instance, to verify an error
distance for the 24-hour forecast, a best track must be avail-
able 24 hours later. If, in that 24-hour period, the storm
dissipated and was no longer identified by a best track
position, the forecast could not be verified. This also
accounts for the fact that fewer cases were verified for
72-hour forecasts than for 48 hours, and fewer 48-hour than
24-hour forecasts. The verifying cases totaled as follows:

24 hours - 4809 forecasts
48 hours - 3038 forecasts
72 hours - 1372 forecasts

The following parameters were also analyzed for each forecast
initiation time:

1. Maximum wind
2. Latitude
3. Longitude
4. West-east component (positive to the east) of
    tropical cyclone movement
5. South-north component (positive to the north) of
    tropical cyclone movement

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[2]A post-analysis set of positions and maximum winds based
on all available information.

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6.   Position number on storm track (related to warning number and length of existence of storm)

7.   Number of storms in progress at forecast time

8.   Month

9.   Error distance (forecast position to best track position)

10. Direction from forecast position to best track position

The 1976 data was processed in a similar manner, but retained separately for independent testing. In this data set there were 625 best track positions at six-hourly intervals for 25 tropical cyclones and the verifying cases totaled:

24 hours - 524 forecasts

48 hours - 424 forecasts

72 hours - 332 forecasts

The 1966-1975 basic data set was then examined by stepwise multiple linear regression and discriminant analysis techniques to determine basic statistical relationships between parameters and find parameters related to forecast errors. The results were then tested on the 1976 data set. The results of the statistical analysis were also used to examine the year-to-year variation in forecast accuracy as well as the trend during the 11-year period.

3. DISCUSSION OF RESULTS

3.1 Linear Regression and Correlation Analysis

The initial statistical analysis of the variables employed the UCLA Biomedical computer program BMD02R stepwise multiple linear regression (Dixon, 1970). Tables 1 and 2 summarize the means, standard deviations, variances explained, and the correlation matrix of the first nine variables discussed above for the 24-, 48- and 72-hour forecasts. The maximum coefficient of any available predictor on the magnitude of the forecast error (at either 24, 48 or 72 hours) was 0.185. However, many of the correlations were significant on the 1% level. The maximum total explained variance of the error distance was less than 11%. The variables contributing most to the explained variance were the maximum wind, latitude, longitude, west-east movement and south-north movement. The concept of predicting the error was then oriented toward a discriminant analysis where forecasts could be identified, and hopefully forecast, as either "good" or "bad." This will be discussed later.

3.2 Trends

In order to examine the forecast errors in more detail, the errors were stratified and mean errors were computed for each stratification along the range of each variable. Significant trends were evident.[3] In the analysis, stratifications were selected to keep the number of cases in each group relatively high. Frequencies are typically a few hundred and are not indicated except where they drop below 100. As an aid in interpreting the forthcoming figures, relative frequencies,

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[3]*Trends to be discussed were subjected to "t" tests and most were shown significant at least at the 5% level with some at the 1% level.*

Table 1. Basic statistical information of the stepwise multiple linear regression analysis (1966-1975 data).

VARIABLE	MEANS	STANDARD DEVIATION	VARIANCE EXPLAINED (%)		
			24-HR	48-HR	72-HR
MAXIMUM WIND ms^{-1} (kt)	33.9 (65.9)	14.8 (28.8)	1.7	0.7	0.2
LATITUDE (°N)	18.7	6.3	4.2	1.1	0.6
LONGITUDE (°E)	135.0	14.6	1.8	2.3	2.3
WEST-EAST MOVT ms^{-1} (kt)	-2.8 (-5.5)	3.3 (6.4)	0.1	1.7	1.5
SOUTH-NORTH MOVT ms^{-1} (kt)	2.0 (4.0)	2.1 (4.1)	0.3	0.3	0.1
POSITION NUMBER	13.5	10.6	NE	NE	NE
NUMBER OF STORMS	1.5	0.7	0.3	0.2	NE
MONTH	8.7	2.3	NE	NE	0.1
24-HR FORECAST ERROR: km (n mi)	233 (125.7)	150 (80.8)			
48-HR FORECAST ERROR: km (n mi)	458 (247.0)	285 (153.8)			
72-HR FORECAST ERROR: km (n mi)	685 (369.4)	419 (226.0)			
TOTAL VARIANCE EXPLAINED (%)			10.5	8.8	6.6

NE: Was rejected in linear regression

Table 2. Correlation matrix for the 24-, 48- and 72-hour forecast error data (1966-1975).

	MAX WIND	LAT	LONG	WEST-EAST MOVT	SOUTH-NORTH MOVT	POS. NO.	NO. STM.	MONTH	24-HR FCST ERROR	48-HR FCST ERROR	72-HR FCST ERROR
MAX WIND	1.000	.177*	.024	-.062	.153*	.397*	.022	.095*	-.185*	-.102*	-.052
LAT		1.000	.116*	.354*	.284*	.367*	.130*	.069	.169*	.173*	.131
LONG			1.000	.119*	.084*	-.130*	.061	-.001	.152*	.164*	.167*
WEST-EAST MOVT				1.000	.117*	.161*	.063	-.077*	.150*	.182*	.171*
SOUTH-NORTH MOVT					1.000	.017	-.043	-.066	.101*	.094*	.061
POS. NO.						1.000	.072	.018	-.053	-.003	.014
NO. STM.							1.000	.049	.073	.075	.045
MONTH								1.000	-.019	.007	-.034

*Correlations significant at the 1% level based upon "t" test with sample size reduced to 1/4 of true size to account for sample dependence after procedure described by Brooks and Carruthers, 1953.

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all based on 4809 cases, are shown for the 24-hour forecasts.
Since they are in percentages of the total, the distributions
roughly apply also for 48- and 72-hour forecasts.

3.2.1 Geographic Position

In each of the 24-, 48- and 72-hour forecast situa-
tions, the mean forecast errors were minimal at lower
latitudes (Fig. 1(a)), gradually increasing with latitude.
This indicates, as expected, that storms are more accurately
forecast before they recurve and move into higher latitudes.
Mean forecast errors decrease with decreasing east longitude
(Fig. 1(b)). Generally, a forecast for a storm in a more
westerly position is one based on a longer than average
history, and is in an area of better synoptic data and land
radar coverage, given the proximity to the Philippines, Taiwan,
and China, and other continental areas west of 130E.

The geographic variations of mean 24- and 48-hour fore-
cast errors can be seen in Fig. 2. This figure dramatically
shows, for example, the difference between tropical cyclone
forecast errors for tropical cyclones affecting the Philippines
versus those affecting the Japan/Korea area.

3.2.2 Maximum Wind

Maximum wind is another important parameter. As
shown in Fig. 3, the mean errors decrease with increasing
maximum wind speeds, indicating that better developed tropical
cyclones are more accurately forecast. It should be noted
that better developed tropical cyclones are generally ones
with longer histories and more accurate center locations.
These influences will be discussed later. This general trend
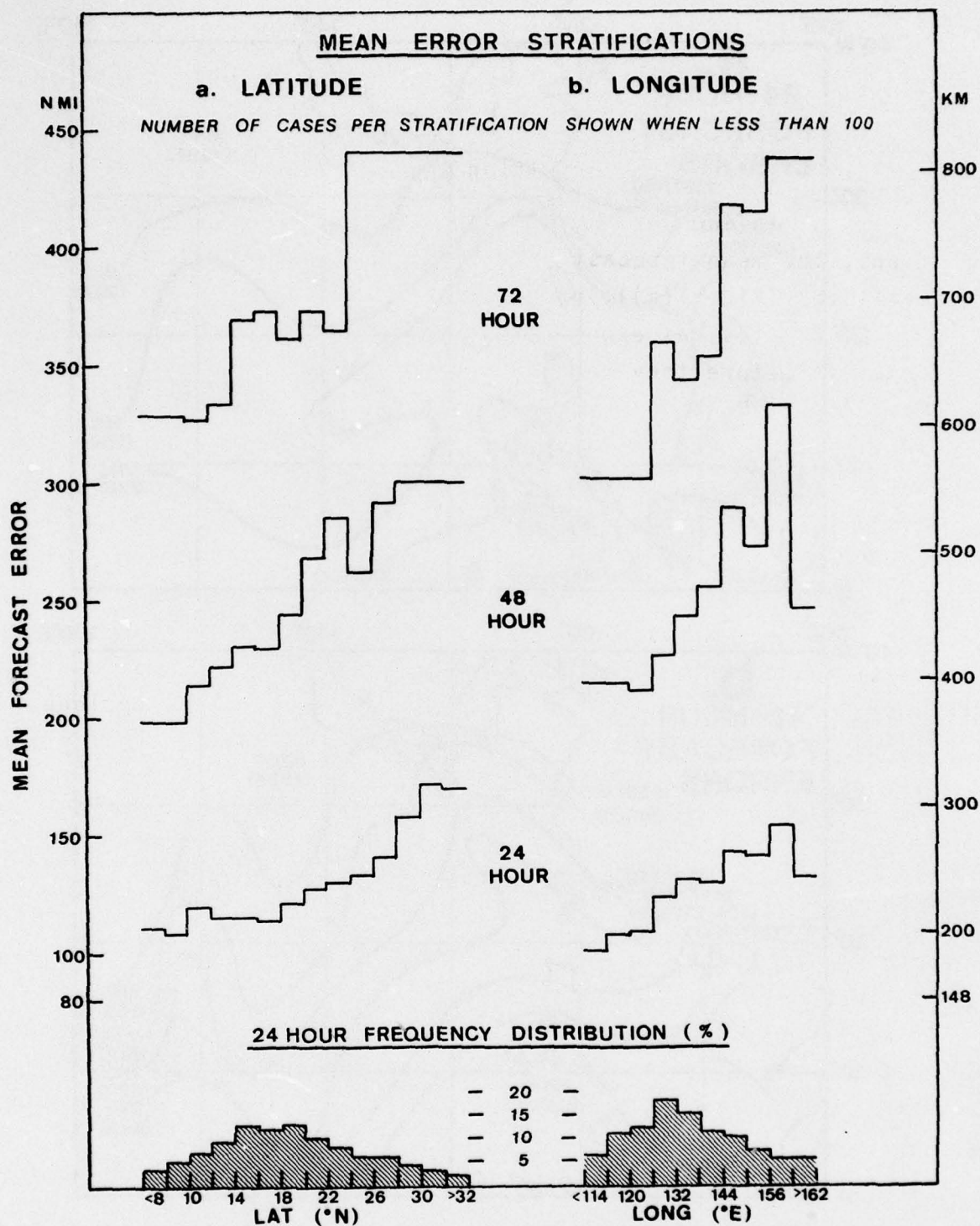between forecast error and maximum wind is visible for all
three forecast times.

Figure 1. Mean error stratifications by latitude (a) and
longitude (b).

a.
24-HOUR FORECAST ERRORS

40°N 100° 120° 140° 160°E

>160
(>297)

(297)160
(259)140
(222)120
(185)100

160
(297)

<100
(<185)

140
(259)

100
(185)

120
(222)

<100
(<185)

120(222) 100(185) 100(185)

30°
20°
10°
0

b.
48-HOUR FORECAST ERRORS

40°N 100° 120° 140° 160°E

(556)300
(519)280

>300
(>556)

(482)260
(445)240
(408)220
(371)200

300
(556)

280
(519)

260
(482)

240
(445)

<200
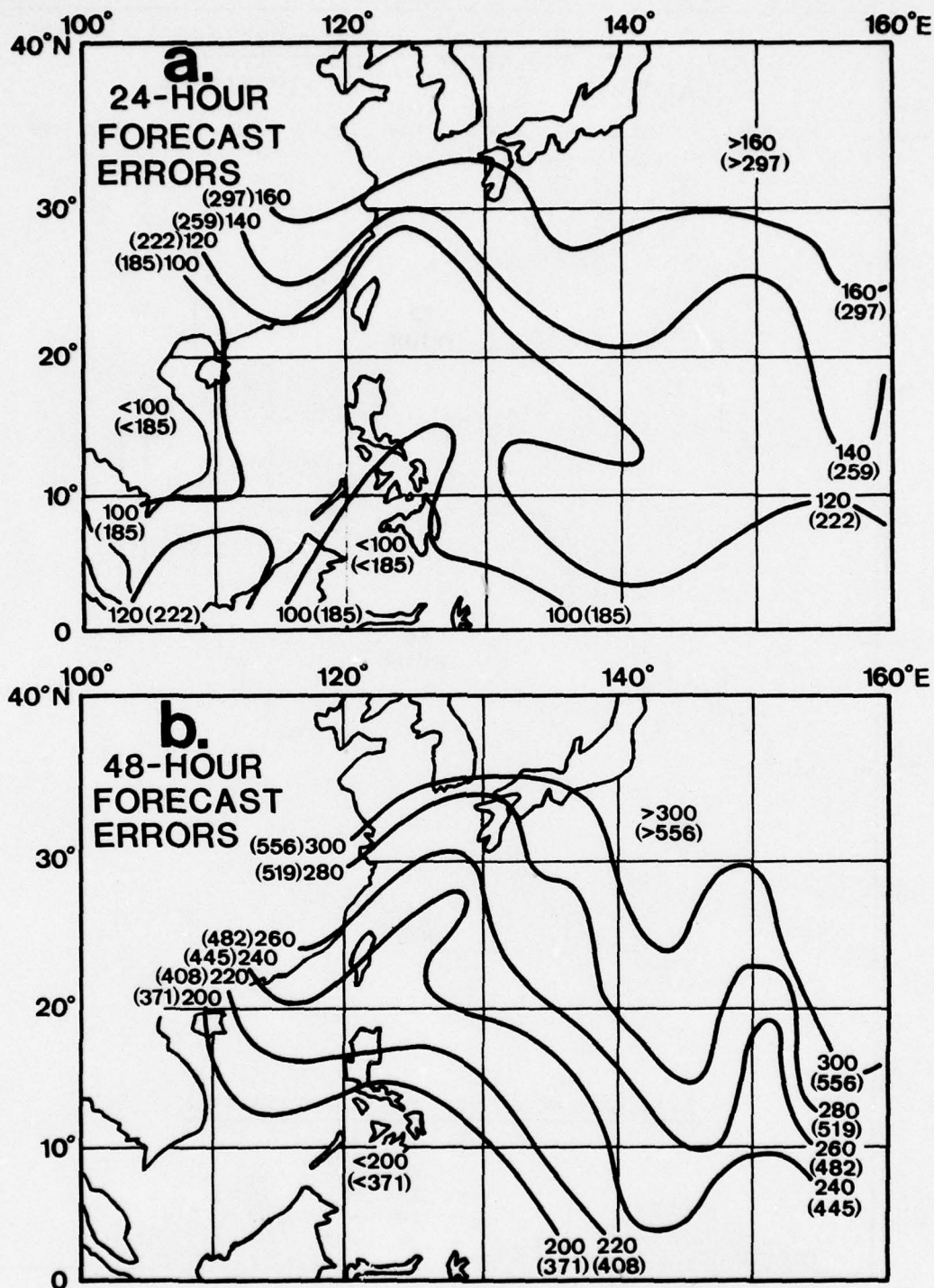(<371)

200 220
(371)(408)

30°
20°
10°
0

Figure 2. Geographic distribution of mean 24-hour (a) and
48-hour (b) forecast errors for western North Pacific
tropical cyclones. Errors are based on 1966-1975 data
and relate to mean forecasts from initial positions.
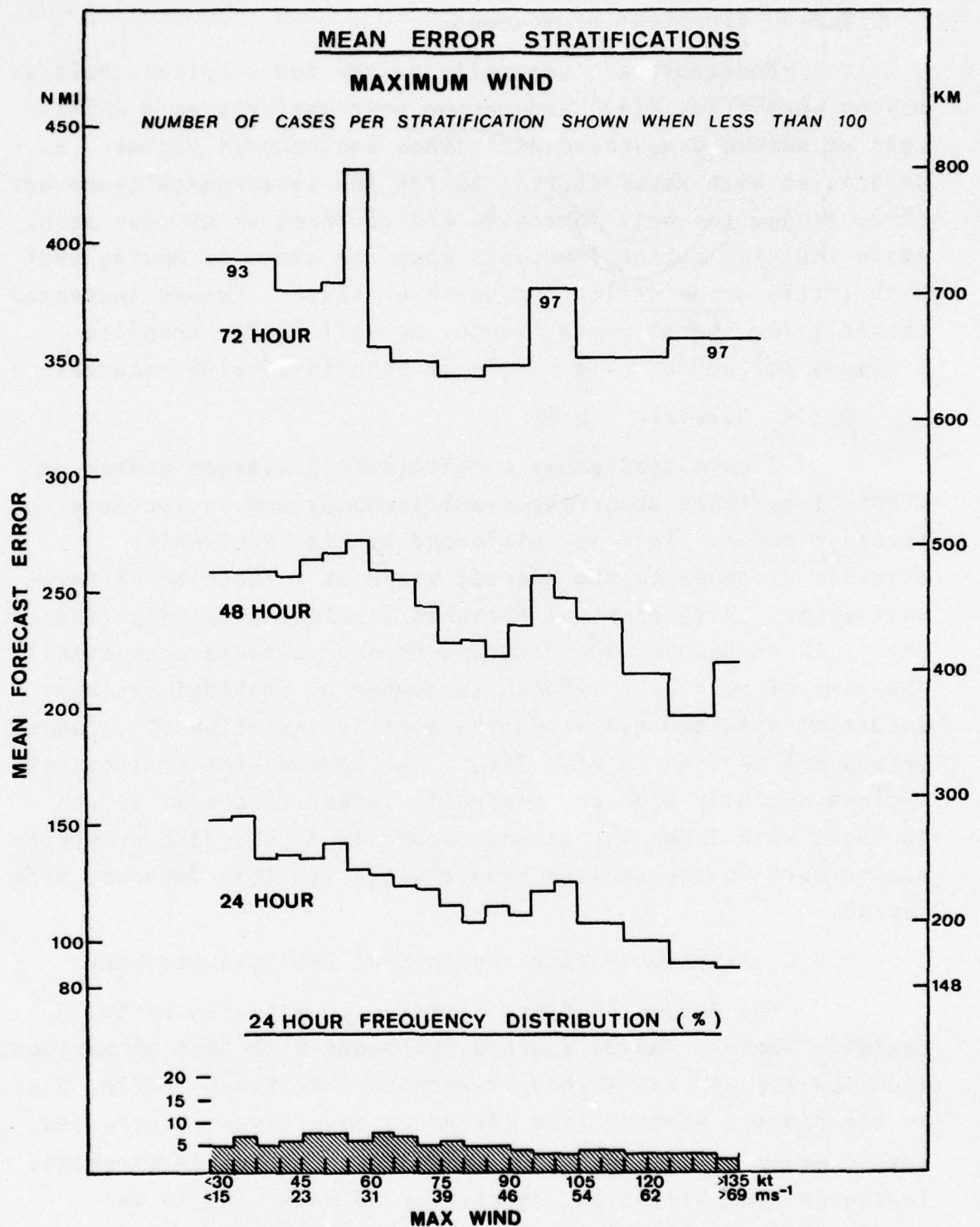Values are given in km ( ) and n mi.

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Figure 3. Mean error stratifications by maximum wind.

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3.2.3 Direction of Movement

Forecasts are generally better for tropical cyclones moving west (Fig. 4(a)) and become progressively more difficult as westward movement diminishes and becomes eastward as associated with recurvature. As for the south-north component (Fig. 4(b)), the best forecasts are centered at or near zero, again implying better forecasts when the storm is moving west with little or no deflection north or south. Errors increased markedly for storms moving south, as well as for tropical cyclones moving north, as would be associated with recurvature.

3.2.4 Multiple Storms

Figure 5(a) shows a relationship between number of tropical cyclones occurring simultaneously and an increase in forecast error. This is reinforced by Fig. 5(b) which examines distance to the nearest storm as a function of forecast error. With tropical cyclones in close proximity (less than 1112 km [600 n mi]) forecast errors increase dramatically. The time of year also relates to number of tropical cyclones occurring simultaneously and the monthly variation of forecast errors can be seen in Fig. 5(c). The peak months of tropical cyclone activity produces generally larger errors at 24 and 48 hours with large variations occurring in the 72-hour errors due in part to the smaller sample sizes for this forecast time period.

3.2.5 Position Number and Initial Position Accuracy

The length of storm history, as measured by the position number, showed a trend congruous with that of maximum wind for the 24- and 48-hour forecasts. As shown in Fig. 6(a), as the storm's history (and therefore development) increased, the forecast errors decreased. This error trend is strongest in the 24-hour situation, decays for 48 hours and is not apparent at all for 72-hour forecasts as might be expected
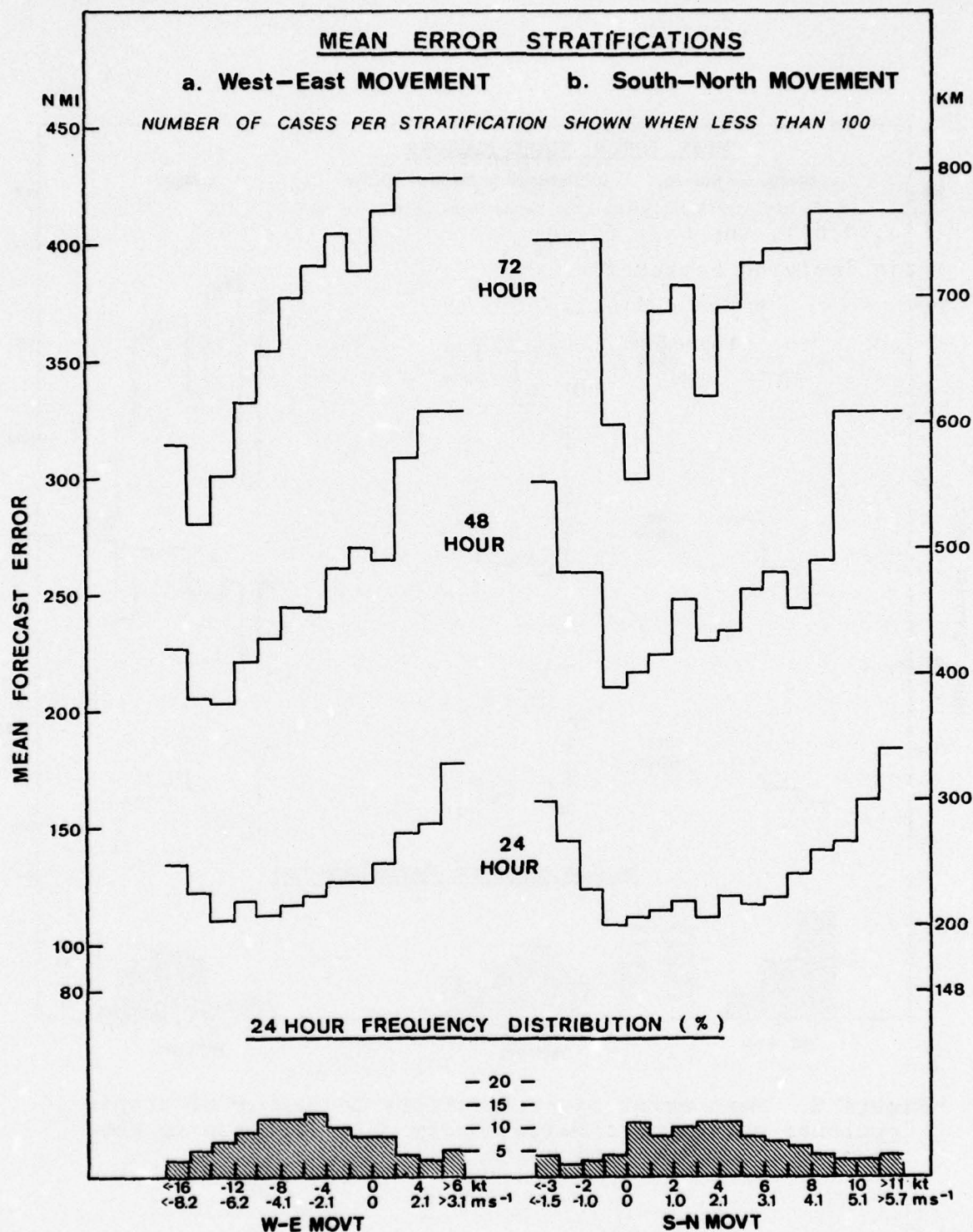
Figure 4. Mean error stratifications by west-east (a) and south-north (b) components of movement.
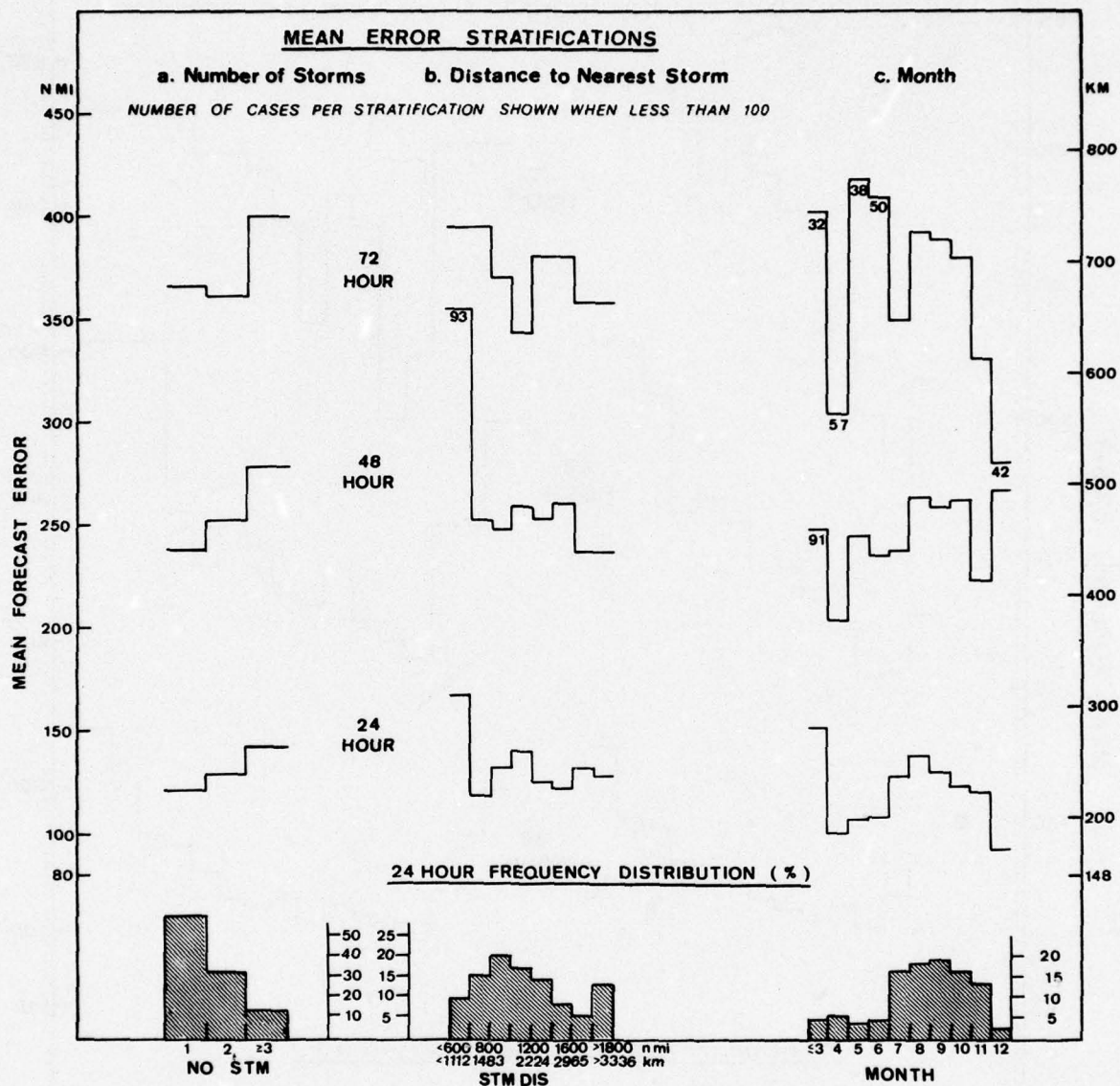
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Figure 5. Mean error stratifications by number of tropical cyclones occurring simultaneously (a); distance to the nearest storm (b); and month (c).
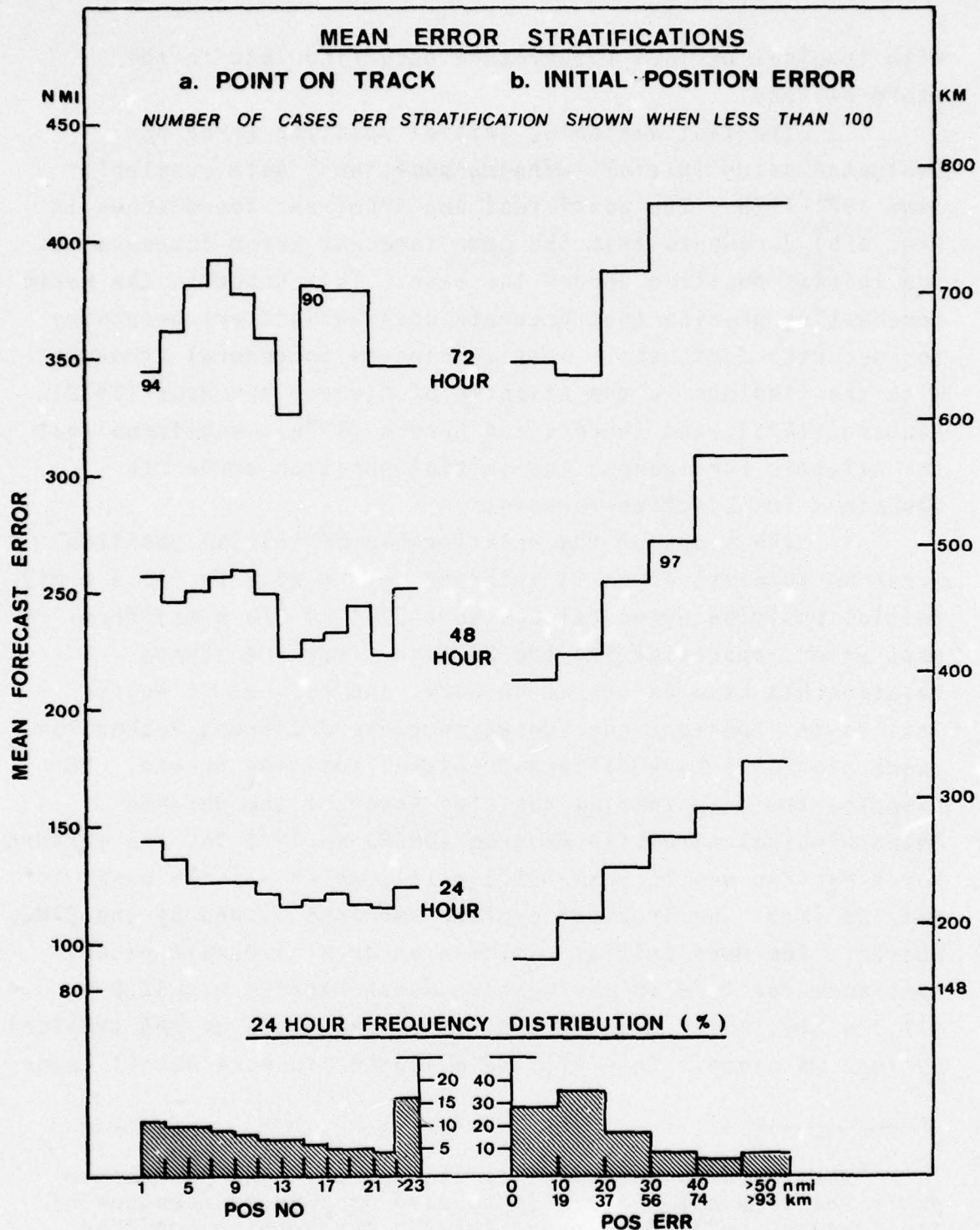
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Figure 6. Mean error stratifications by point on track
(position number which is related to life cycle or
length of existence of tropical cyclone) (a) and
initial position error (b).

with tropical cyclone recurvature occurring late in the storm history.

The last variable, initial position error was evaluated using initial "warning position"[4] data available from 1971-1975. The consistent and prominent trend shown in Fig. 6(b) documents that the mean forecast error increases as the initial position errors increase. This supports the basic forecasting premise that accurate observations are necessary for accurate forecasts. This finding is in general agreement with the findings in the Atlantic of Neumann and Hope (1972), Neumann (1975), and Sanders and Gordon (1976), who found that for Atlantic hurricanes, the initial position error was important in objective forecasts.

The slope of the relationship of initial position error to forecast error is interesting. A 23.2 km (12.5 n mi) initial position error relates to a 37.1 km (20 n mi) forecast error, approximating the 24-hour slope. A strong relationship also exists at 48 hours and even at 72 hours. This is an important consideration since different reconnaissance platforms have different initial position errors. For example, the mean initial position error of the Defense Meteorological Satellite Program (DMSP) in 1976 for the western North Pacific was 56.5 km (30.5 n mi), which was the basis for some 30.4% of the tropical cyclone warnings issued by the JTWC. Whereas, the mean initial position error of aircraft reconnaissance for 1976 in the western North Pacific was 32.8 km (17.7 n mi), which was the basis for some 44.3% of the tropical cyclone warnings. This will be discussed in more detail later.

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[4]The "warning position" is the position the forecaster feels the tropical cyclone is located at time of issuance of the forecast. The difference between the warning position and the post analysis best track position is the initial position error.

3.3 Autocorrelations

To this point, the forecasts (and hence forecast errors) have been tacitly assumed to be independent of each other. In reality, successive six-hourly forecasts for a particular storm are strongly correlated. This can be seen in Table 3 which gives the estimated autocorrelation coefficients between errors from successive forecasts with lag times out to 36 hours. In general, it can be seen that autocorrelations at any given time lag increase as the forecast interval increases.

Table 3. Autocorrelations between forecast errors
of successive forecasts.

TIME LAG (HOURS)	24-HR	48-HR	72-HR
0	1.000	1.000	1.000
6	.665	.790	.838
12	.432	.587	.675
18	.291	.432	.476
24	.213	.305	.371
30	.173	.212	.127
36	.181	.171	.177

3.4 Discriminant Analysis

The UCLA Biomedical computer program BMDP7M (Dixon, 1975) was used to attempt to discriminate between forecasts likely to produce large errors and those likely to produce small errors. The cases were classed in three groups according to their known 24-hour errors. Group 1 consisted of cases where the magnitude of the error was less than the median in both W-E and S-N components. Group 2 had one component above the median and the other below the median while Group 3 had both components above the median. The percentage of cases falling into Groups 1, 2 and 3 was 30%, 46% and 24%, respectively.

The discriminators made available for the analysis were those variables previously discussed which were shown to be related to error magnitude and would be known to the forecaster as he made his forecast. These were: (1) latitude; (2) longitude; (3) maximum wind; (4) number of storms in progress; (5 and 6) the two components of motion over the previous 12 hours; (7) month; and (8) distance to the nearest "other" storm, if one was present otherwise a large default number was assigned. Of the above parameters, the first six were selected by the analysis program as significantly contributing to discrimination.[5]

Typically, Group 1 was characterized by well developed tropical cyclones (typhoon intensity) in the western part of the region at low latitudes and moving generally west. A Group 3 forecast was typical during or after recurvature and included the total spectrum of tropical cyclone intensities. Group 2 included many low latitude weak depressions or tropical cyclones of all intensities at or near typical recurvature latitudes but not as yet exhibiting recurvature. Also included in Group 2 were many otherwise Group 1 cases in multiple storm situations.

The forecast error distributions are illustrated in Fig. 7 by means of 40% probability ellipses bases on the assumption of a bivariate normal probability distribution.[6] Ellipses are given for each group for 24-, 48- and 72-hour forecasts although the discriminant analysis was based on 24-hour errors only. The most prominent difference in the three sets of ellipses is their size. The area within each

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[5]*The resulting classification functions are shown in Appendix A.*

[6]*For comparison purposes, 70% and 90% probability ellipses relate to distributions 1.55 and 2.15 times, respectively, the axis values depicted by Fig. 7.*
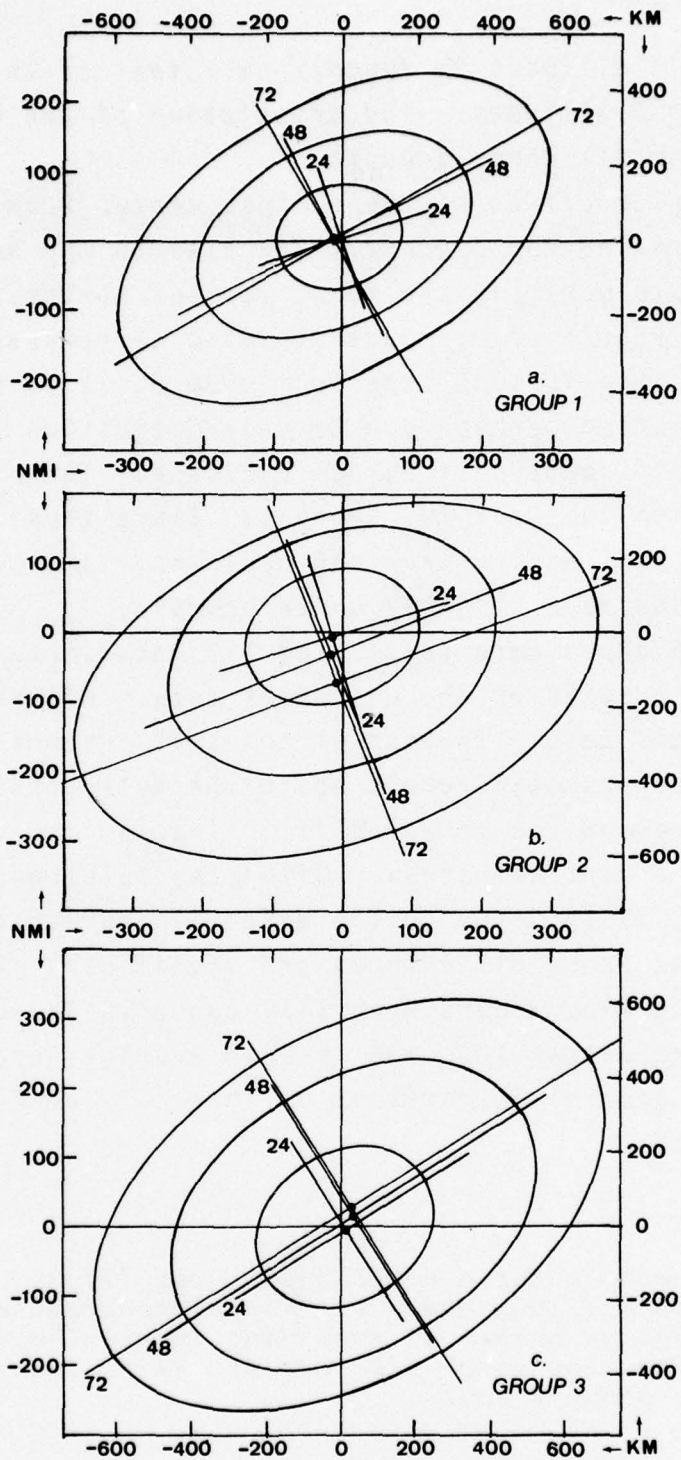
Figure 7. The 40% probability ellipses for each forecast
interval for (a) Group 1; (b) Group 2; and (c) Group 3
forecasts. The origin is the forecast position with
each ellipse center the average verifying position
relative to forecast position.

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of the Group 1 ellipses is roughly half that of the corresponding Group 3 ellipses. The orientation of the major axis is similar for all three groups.

The bias or offset of the ellipse center from the diagram origin is striking for Group 2. The bias to the southwest means forecasts were, in the mean, too far northeast. This could be the result of over anticipation of recurvature.[7] Although the bias is much less for Group 3, it is in the opposite direction perhaps due to underestimation of the acceleration of recurved tropical cyclones. The bias is small but slightly to the west for Group 1. Since these are basically east to west moving tropical cyclones, this would indicate speed is in the mean slightly underforecast.

The 1976 cases were tested for fit into various probability ellipses constructed on the dependent data. Figure 8 shows the results of this test. In each of the small graphs the 45° line represents the expected result while the dots connected by line segments represent the observed fit. The maximum deviation is indicated by a vertical arrow. Using the Kolomogorov-Smirnov test (Massey, 1951) based on the effective number of independent cases, none of these differences are significant at the 5% level.[8] The ellipses were generally conservative because 1976 forecasts were better than the 10-year average perhaps reflecting a general improvement of forecasts over the eleven years involved.

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[7] As an example for a single year, the 1967 tropical cyclone season had many east-west moving tropical cyclones with below average number of recurving tropical cyclones. The 72-hour forecast error bias was 172 km (93 n mi) to the southwest for Group 2 cases.

[8] Because of high autocorrelation, the sample size was reduced by 1/4 to account for sample dependence (after Brooks and Carruthers, 1953).
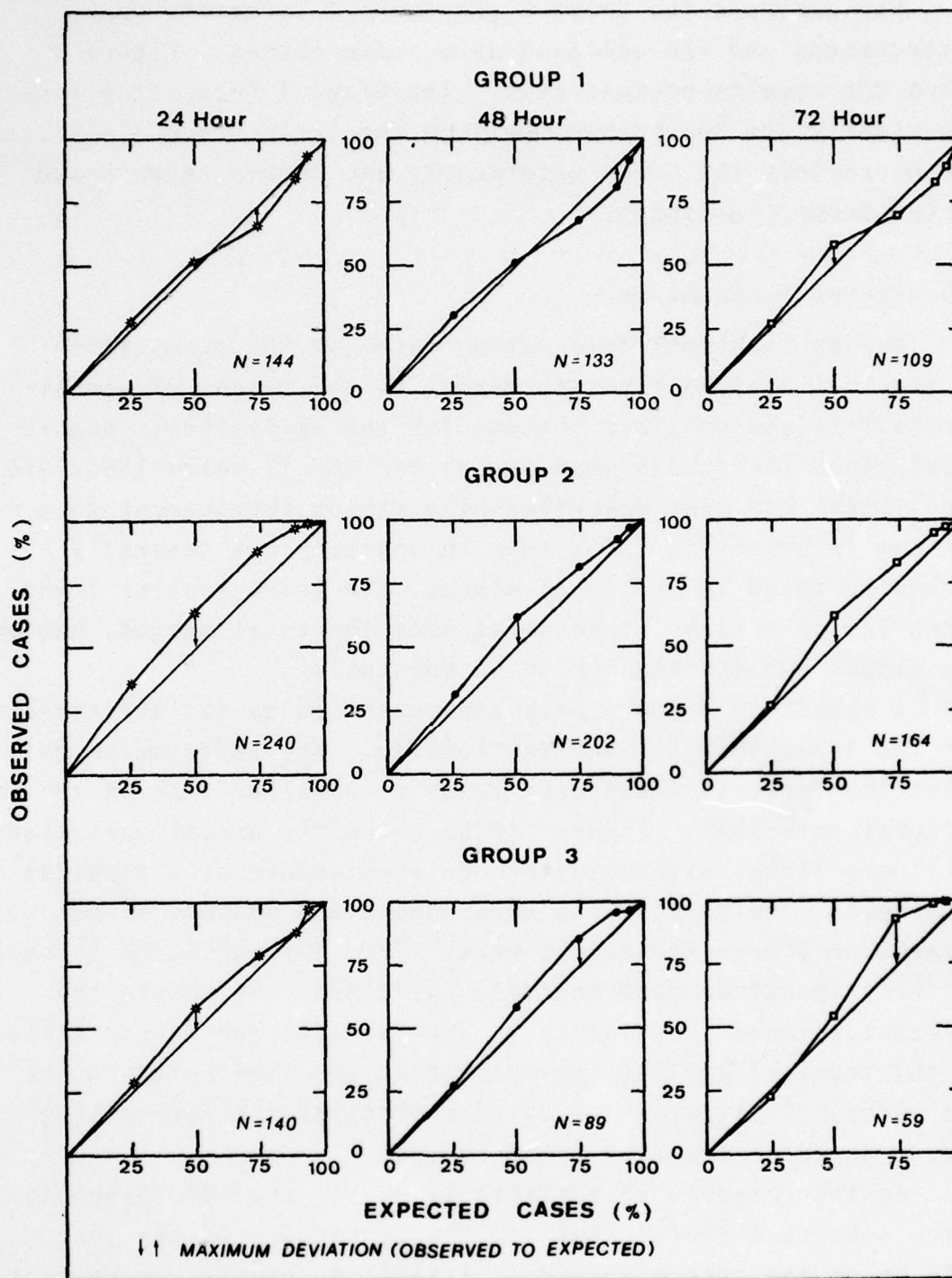
Figure 8. The 1976 verifying positions that fell into 25, 50, 75, 90 and 95% probability ellipses by Group and Forecast (24, 48, and 72 hours). Maximum deviation is indicated by vertical arrow.

For contrast the Group 3 and Group 1 forecasts were interchanged and the ellipses were again tested. Figure 9 shows the results of this test. The Group 1 forecast errors are clearly not represented well by the large Group 3 ellipses and conversely the Group 3 forecasts are poorly represented by the Group 1 ellipses.

3.5 Annual Variability

Perhaps the most interesting facet of the examination of tropical cyclone forecast errors is the extent of annual variability and possible reasons for the variations. Figure 10(a) shows the annual mean errors for the 11 years 1966-1976. The picture has been described as a steady improvement to a minimum in errors in 1970, then an unsteady but generally worsening trend in the years since. The least squares trend lines indicate minor improvement over the total period, however, the slopes are too shallow to be conclusive.

A number of factors have been examined to isolate reasons for the large year to year variability. The performance of objective forecast techniques tends to parallel that of the official forecasts. Figure 10(b) shows the annual variation of simple linear extrapolation, or persistence as a forecast technique. The persistence error depicts a measure of how well behaved or linear the tracks were. This extrapolation is based on "best track" or post analysis positions. Of course the forecaster faces uncertainty in the location and recent history of the tropical cyclone, nevertheless, the similarity in the two curves illustrates the vulnerability of the forecasting system to major track or speed changes.

Another measure of variability is the type of forecasts which make up a year. That is, the percentage of the year made up of the type expected to give large errors versus those expected to give small errors. In Fig. 10(c), the annual mean
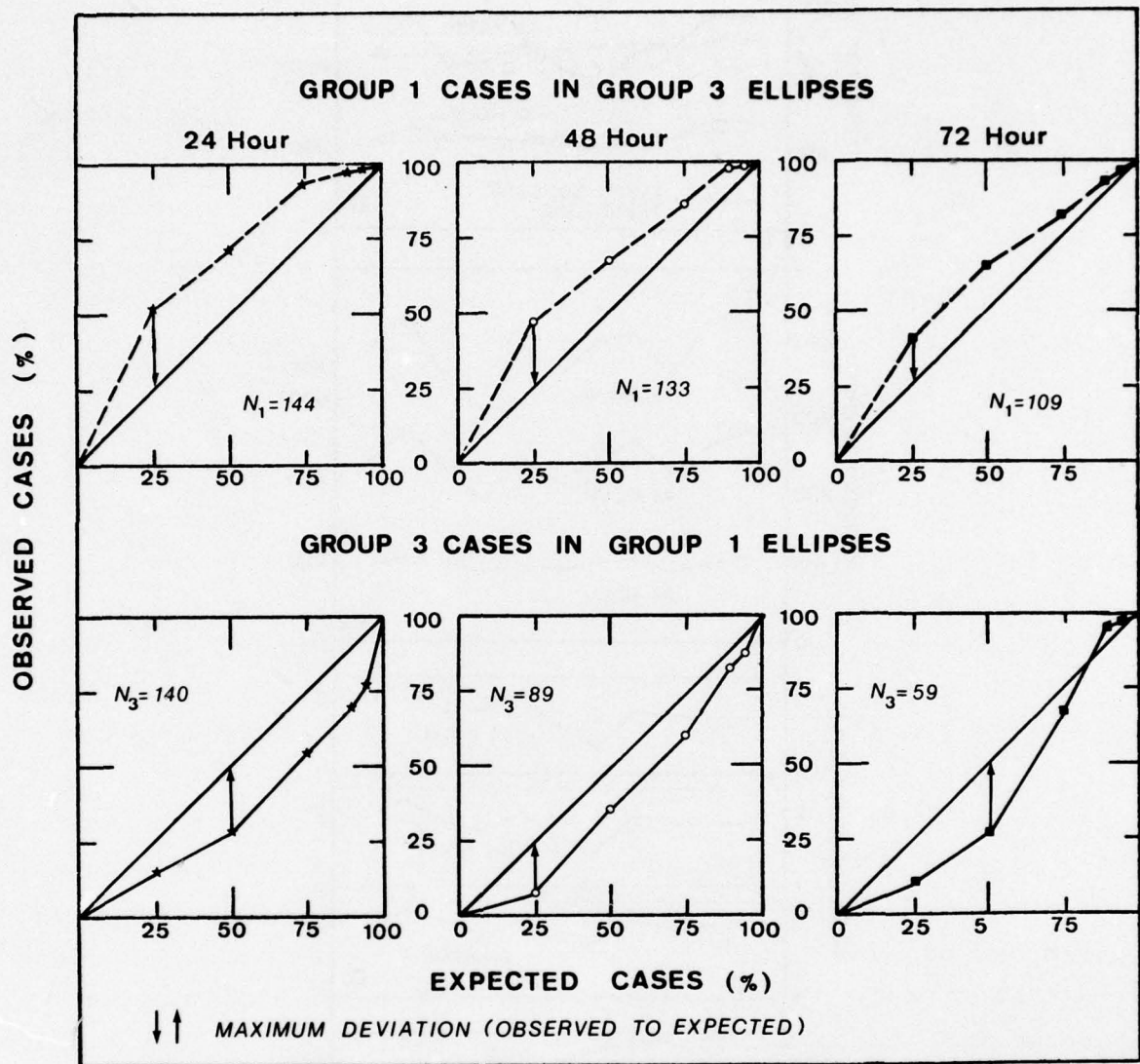
Figure 9. The 1976 verifying positions that fell into 25,
50, 75, 90 and 95% probability ellipses for Group 1 into
Group 3 ellipses and Group 3 into Group 1 ellipses for
24, 48, and 72 hours. Maximum deviation is indicated by
vertical arrow.

Figure 10. The annual variation of (a) mean tropical cyclone official forecast error; (b) mean persistence error; (c) mean Group number; (d) percentage of warnings based on reconnaissance and satellite; and (e) number of JTWC duty officers.

group numbers are shown. This comes from the discriminant analysis previously described where Group 1 represents a relatively easy forecast and Group 3, a difficult forecast. For exampl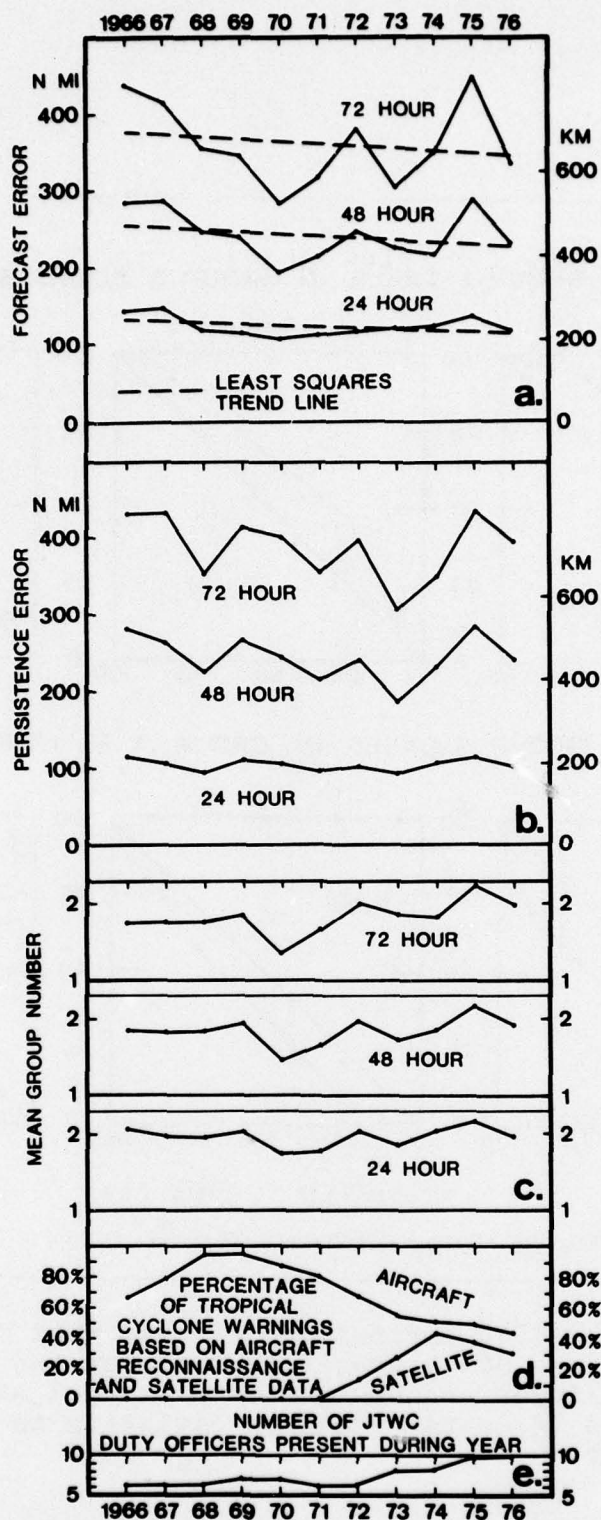e, 1970 was dominated by Group 1 forecasts and the mean group number is well below 2.0. The 1975 season was dominated by the difficult Group 3 forecasts and the mean group number is above 2.0. The general characteristics of the curves of Fig. 10(c) follow those of Fig. 10(a), particularly from approximately 1968 or 1969 to 1976.

Figure 10(d) shows the percentage of warnings issued by the JTWC based on aircraft reconnaissance and satellite data. There is qualitative correspondence between large percentages of warnings based on reconnaissance in the middle years and generally lower forecast errors. Forecast errors are larger with the lower percentage of warnings based on reconnaissance data in the early years and the later period. In the years after 1971 satellite data has to some extent replaced reconnaissance, but as indicated previously initial position error is highly related to forecast error and the initial position error for reconnaissance is less than for satellite data. For 1976 the initial position error was 32.8 km (17.7 n mi) for aircraft reconnaissance versus 56.5 km (30.5 n mi) for DMSP.[9] It seems apparent that the reduction of aircraft reconnaissance has had an impact on the forecast errors. In addition, in the years since 1971, aircraft reconnaissance in the western North Pacific has not had the use of the powerful APS-20 radar which provided excellent tropical cyclone "stand-off" fix capability.

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[9]*It should also be pointed out that the DMSP program has been particularly beneficial or cost saving in the reduction of investigative aircraft missions which are flown when the development or formation of a tropical cyclone is imminent. Investigative missions have been cut over the last four years from about four to one per tropical cyclone, which translates into an annual savings of nearly $1 million (Pilipowskyj, 1977a).*

Another factor which has changed at the JTWC in recent years is numbers of duty officers or forecasters. The number of forecasters has historically been six, the Director, Operations Officer and four duty officers. As can be seen by Fig. 10(e), the number of duty officers present during the year has been increased in recent years. It is certainly not clear that this increase has led to an improvement in forecasting. But the question is: Has there been an improvement in forecasting in recent years? This will be addressed next.

One of the major objectives of this study was to examine the longer term change in the forecasting system. This is useful not only as a basis for evaluating the effectiveness of the system, but serves a more important purpose. Over the next few years the tropical cyclone warning system in the western North Pacific will rely increasingly on dynamic models as a major input. It is then important that a baseline be established for relatively short term evaluation of the system, hopefully to measure improvements, but also as a guard against system degradation.

To establish such a baseline the year to year performance must be normalized or adjusted. Annual mean error is a poor measure of performance because clearly some years are heavily loaded with difficult forecasts and others weighted toward easier forecasts. As a normalizing tool, a measure of difficulty is necessary. The distribution of forecasts into the three groups presented earlier is one possible measure. The 1970 season was heavily dominated by the relatively easy Group 1 forecasts, and 1975 by the difficult Group 3 forecasts. The mean group number explains about 30% of the year-to-year variance in mean error. Another important component of error is how persistent the tracks were. The annual persistence error explains from 30 to 50% of the annual variance. Clearly these two measures are not independent. Their correlations decrease in time from about 0.50 at 24 hours to 0.25 at 72

hours. Another important component of error is the error in the initial position. This error is assumed to he independent of the two previous measures. Initial position error has been documented on a case by case basis since 1971 and annual means are available since 1970. There are other factors such as the introduction of objective techniques, increased knowledge concerning the behavior and characteristics of tropical cyclones, improvements in the mid-latitude prognostic models, data (synoptic and satellite) availability, and changes in personnel. These are less tangible and will for the moment be ignored.

A system of handicapping the annual errors has been devised to adjust for annual forecast difficulty and the variability in initial position error or more specifically reconnaissance support. The first component of the handicapping system is based on a two predictor least squares regression equation. The predictand is annual error (AE in km) and the predictors are the annual mean group number (G) and the annual mean persistence error (P in km) as follows:

$$AE_{24} = -76.4 + 0.779 P_{24} + 79.1 T_{24}, \tag{1}$$

$$AE_{48} = -86.5 + 0.748 P_{48} + 112.8 G_{48}, \text{ and} \tag{2}$$

$$AE_{72} = -227.0 + 0.738 P_{72} + 207.1 G_{72} \tag{3}$$

These equations explain 43, 62 and 79% of the variance in the annual mean errors at 24, 48 and 72 hours, respectively.

The second component of the handicap is based on the percent of forecasts issued where the initial position was based on aircraft reconnaissance. This percentage is known for the 11-year period. This percentage was converted to an equivalent annual mean initial position error by assigning 33.3 km (18 n mi) as the initial position error for reconnaissance based tropical cyclone forecasts (Harrison, 1975 and Pilipowskyj, 1977b) and using the known 7 years of initial

position errors to deduce the initial position error value
based on "other" types of fixes. These "other" types include
land and ship radar, satellite data, extrapolation and synoptic
data. This average was found to be 64.8 km (35 n mi). The
relationship between forecast error (E in km) and initial
position error (E_0 in km) as was shown graphically in Fig. 6(b)
is as follows:

$$E_{24} = 154.3 + 1.6 \, E_0 = 154.3 + 1.6 \, (33.4R + 64.9 \, (1.0-R)), \quad (4)$$

$$E_{48} = 363.2 + 2.4 \, E_0 = 363.2 + 2.4 \, (33.4R + 64.9(1.0-R)), \quad (5)$$

and

$$E_{72} = 617.0 + 2.0 \, E_0 = 617.0 + 2.0 \, (33.3R + 64.8(1.0-R)), \quad (6)$$

where R is the fraction of warnings during the year that were
based on aircraft reconnaissance.

The two handicaps were adjusted by subtracting out the
minimum annual value. The 1973 season for instance, the least
difficult year based on Eqs. (1) through (3), was assigned a
zero handicap for difficulty. In a year when 100% of the
forecasts were based on aircraft reconnaissance, a zero handi-
cap for reconnaissance would have been assigned. Finally the
annual mean errors were reduced by the sum of the two handicap
components. Figure 11 is the "unexplained error." The trend
is more consistent than the error trend of Fig. 10(a)[10] and
reflects in part the "pay-off" or result from research efforts,
i.e., improved forecasting aids and numerical models, and a
better understanding of the tropical cyclone and its surround-
ing environment. Also in the trend line is the result of more
realistic manning of the JTWC in terms of the number of fore-
casters as well as any change in the quality or skill level or

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[10]*The adjusted error-year correlation is approximately
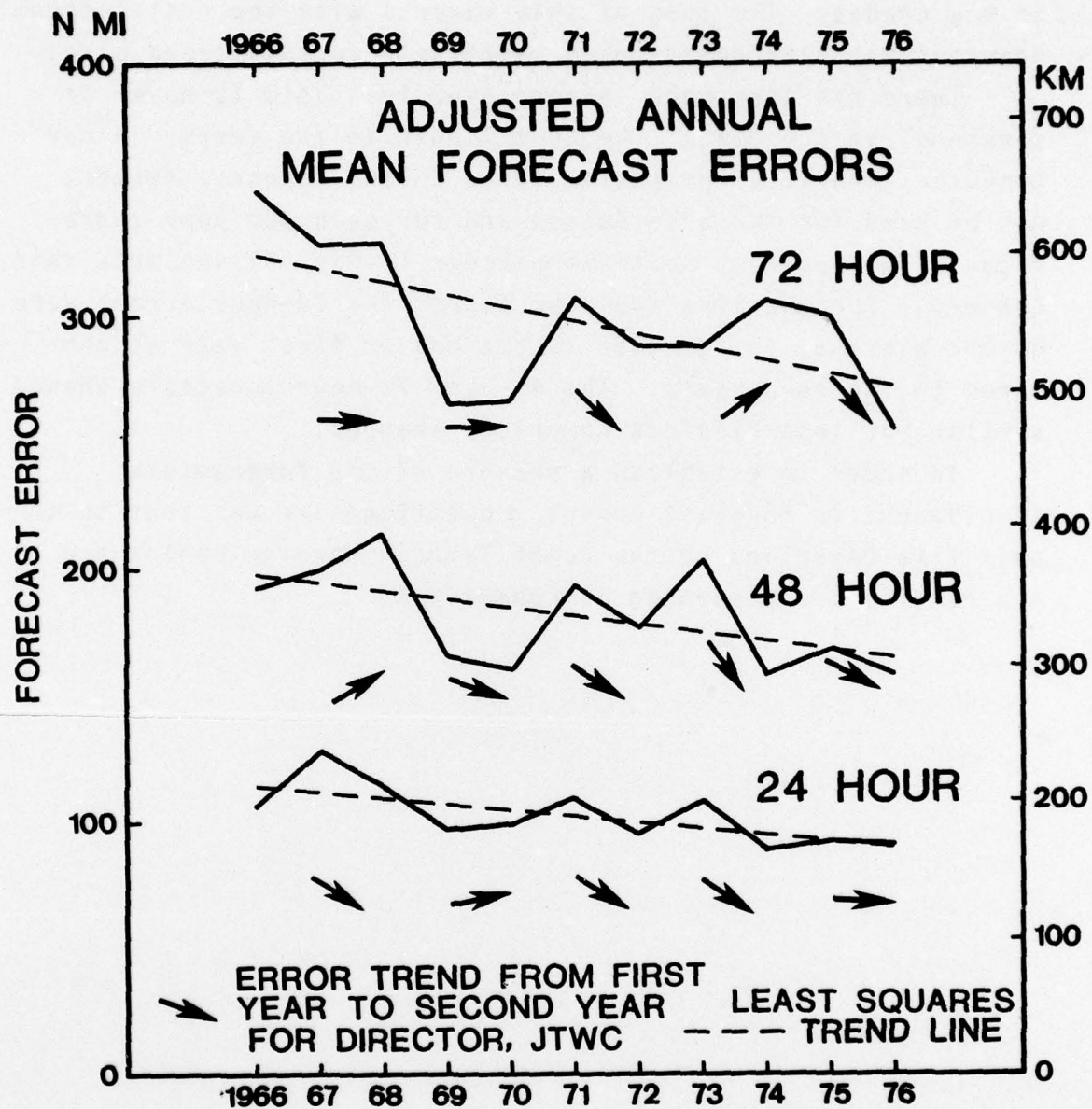0.6 as compared to the actual error-year correlation of 0.3
for Fig. 10(a).*

Figure 11. Annual mean forecast errors adjusted by removal of elements of the annual variation of persistence, forecast difficulty and initial position error.

even motivation of the personnel. Additionally, a rather
steady improvement in satellite support no doubt deserves some
of the credit. The loss of ship reports with the post-Vietnam
drawdown may have contributed negatively to this trend also.

There has long been concern over the rapid turnover of
personnel at the JTWC. The tour length is two years. A new
Director, who is a dominating force in the forecast system,
was on hand for the 1967 season and for each odd year there-
after. The apparent sawtooth pattern in Fig. 11 supports this
concern. For the five two-year tours, the 24-hour errors were,
on the average, 10% greater in the odd or first year as com-
pared to the even years. The 48- and 72-hour forecasts showed
similar but less distinct numerical changes.

In order to establish a measure of the forecasters
involvement in forecast errors, a questionnaire was sent to the
past five Directors of the Joint Typhoon Warning Center and
the results are presented in Appendix B.

4. SUMMARY AND RECOMMENDATIONS

In light of the objectives outlined earlier, for the most part, the goals of the study have been attained. It has been demonstrated that a small number of readily available parameters can, with reasonable effectiveness, classify a tropical cyclone forecast as likely resulting in either markedly above or below average errors. Group 1 forecasts have a high probability of below average errors with a low probability of above average errors. Group 2 forecasts have approximately equal probabilities of being above or below average. Group 3 forecasts have a low probability of below average errors with a higher probability of above average errors. It was found that the error probability ellipses for all three groups are oriented approximately the same (major axis - northeast to southwest), but the area of the Group 1 ellipses was roughly half of the area of the Group 3 ellipses. In addition the year-to-year variation in forecast errors over the past 11 years in the western North Pacific appears to show continued improvement once the errors are adjusted for the annual biases that are present which contribute either negatively or positively to the forecast errors.

The examination of additional parameters could improve the identification of potentially poor forecasts. Initial position error, which was shown to be directly related to forecast errors, was not introduced as a discriminator because it is not generally known to the forecaster at the time of the forecast. In addition, the synoptic patterns associated with the tropical cyclone has not been considered. Parameters which are associated with such features as the Tropical Upper Tropospheric Trough (TUTT), subtropical ridge and transient troughs in the westerlies might prove to be important discriminators especially since they many times relate to the basic problem of tropical cyclone recurvature.

Two primary sources of error are implicit from the statistical analysis: (1) Those related to the recurvature phenomena -- whether to forecast recurvature or not and in the speed of motion after recurvature; and (2) those errors associated with initial positioning. Research aimed at these sources offers considerable potential for improvement in tropical cyclone forecasting. The greatest hope for the solution of the recurvature problem may lie with dynamic models, but synoptic and statistical studies should not be ignored.

The positioning problem suggests improvement in the reconnaissance system. While more and better equipped aircraft is a possible, and perhaps expedient solution, developments in the satellite area may be the ultimate solution. This may involve finding a different and more conservative way to define the location of a tropical cyclone other than the so-called eye or estimated center.

A further application of the statistical base presently established would be to derive "threat" or "strike" probabilities for specific locations in the western North Pacific. For example, Fig. 12 gives the probability integrated over an area 139 km (75 n mi) to the left and 93 km (50 n mi) to the right of Kadena Air Base, Okinawa relative to the forecast track of Typhoon Fran. The integration is also performed over time from that initial time of 1800 GMT, 7 September 1976 to a time 12, 24, 48 and 72 hours later.

In addition, another application would be to derive forecast probability ellipses (such as 50, 75 and 95%) for specific forecast positions out to 72 hours. This could even be carried a step further by adding information such as the radius to the 15.4 ms^{-1} (30-kt) wind or 3.7 m (12-ft) sea to attain a probability for these parameters to aid tropical cyclone avoidance and decision making.
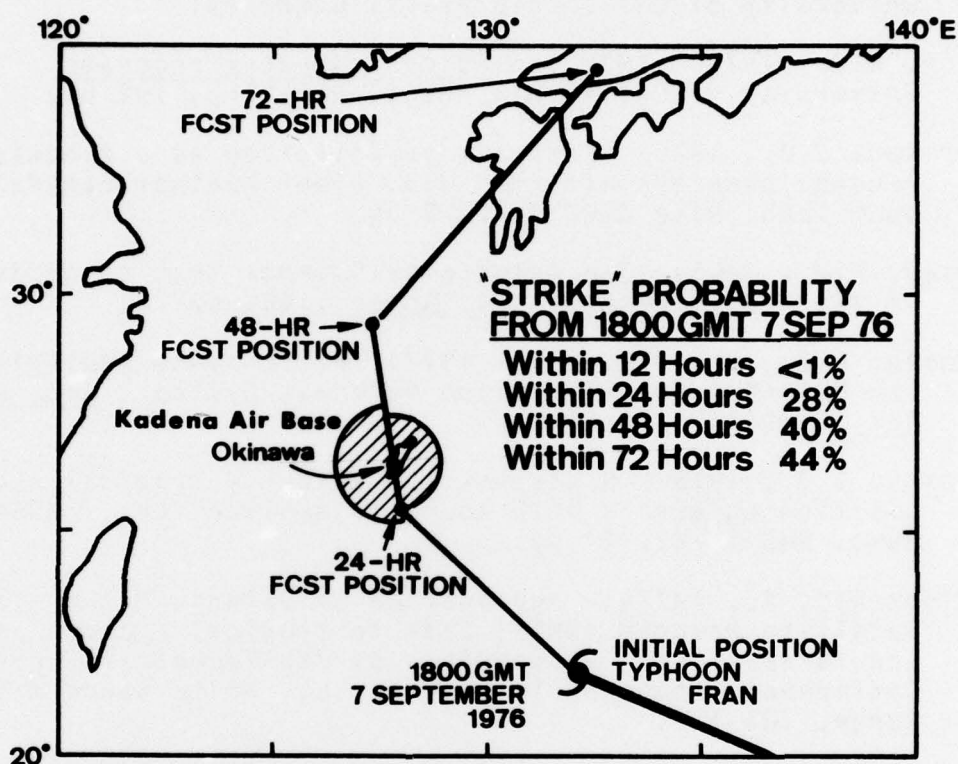
Figure 12. The "strike" probability of Typhoon
  Fran (1800 GMT, 6 September 1976) passing
  through the shaded area relative to Kadena Air
  Base, Okinawa. The probabilities are based on
  the forecast track and the error distributions
  for this type of tropical cyclone. Typhoon
  Fran did in fact miss the shaded area as the
  storm passed to the east of Okinawa.

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APPENDIX A

The discriminate analysis resulted in three functions
which are linear combinations of six variables as follows:

COEFFICIENTS

VARIABLE	FUNCTION 1	FUNCTION 2	FUNCTION 3
Latitude (deg)	-0.06439	0.08352	0.04238
Longitude (deg)	-0.03231	0.00274	-0.03928
Maximum Wind (ms^{-1})	0.04371	0.02694	-0.00239
S-N Movt (ms^{-1})	-0.15719	0.20958	-0.06587
W-E Movt (ms^{-1})	-0.04932	-0.18310	0.01311
Nr. Storms in Progress	-0.26096	0.01186	1.05585
Constant	4.66511	-3.81310	3.14344

The values of the functions at the group mean for each variable
are as follows:

	FUNCTION 1	FUNCTION 2	FUNCTION 3
Group 1	0.36059	0.05017	-0.01138
Group 2	-0.04093	-0.07138	0.01688
Group 3	-0.36186	0.07454	-0.01822

In order to determine which group a forecast would fall
into, each of the functions f_i for i = 1, 2, 3 are evaluated
using the known actual values for the six variables. A
squared distance is then determined from the group mean value
($u_{i,k}$) for the 3 functions (i) and the three groups (k = 1,2,3)
with the following equation,

$$D_k^2 = \sum_{i=1}^{3} (f_i - u_{i,k})^2 .$$

The forecast is assigned to the group (k) corresponding to
the minimum D_k^2 value.

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APPENDIX B

One parameter that is difficult to quantify is the "man" or "woman" involved in the day to day forecasting of tropical cyclones. In order to establish a measure of his or her involvement in the forecast errors, a questionnaire was forwarded to the past five Directors of the Joint Typhoon Warning Center and the responses are summarized below:

1. <u>How long does it take to become a "very good" tropical cyclone forecaster (typhoon duty officer)</u>?

The range of answers was extremely large -- from two years to eight years. Although the term "very good" can be interpreted a number of ways, most felt that this level could be closely achieved in 3-4 years if the individual really worked hard on developing his or her proficiency.

2. <u>Does ability continue to improve or level off</u>?

The general response indicated that if the individuals motivation and effort remained high, improvement would be dramatic the first 2-3 years and then taper off. Since ability was related to experience, the ability to predict the unusual event would continue to increase.

3. <u>What are the characteristics and backgrounds of the "better" tropical cyclone forecasters</u>?

The characteristics would include: (a) a high level of motivation, perseverance, perfectionism and imperturbability; (b) the ability to integrate data from a variety of sources into a forecast; (c) an avid reader of technical literature with the willingness to test and evaluate new techniques; and (d) the ability to understand the limitations of objective techniques and numerical or dynamic model output.

The background should include good training and operational experience in tropical meteorology or 3-5 years operational experience in extratropical meteorology. Formal education, prior research experience and a technical background in aircraft reconnaissance or satellite data applications would be relevant but less important.

4.   Would permanent tropical cyclone forecasters do a better job than the present two year military tour?

Four out of 5 answers indicated "yes," with one suggestion for having a 3 season military tour which would be an improvement from the present system and with some exceptional duty forecasters extended to a fourth season. Another suggested having a permanent chief forecaster (civilian) to maintain continuity, to develop extensive expertise and to train newly assigned forecasters.